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Nacelle lidar for power perf. – the UniTTe approach to retrieve V

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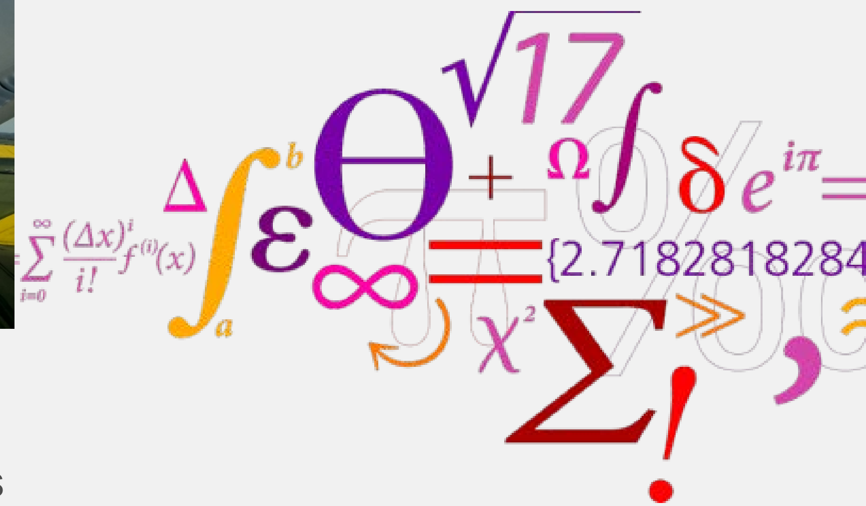
Nacelle lidar for power perf. – the UniTTe approach to retrieve V∞



A. Borraccino, R. Wagner

IEA Wind task 32 – workshop nacelle lidars
27th September 2017

DTU Wind Energy
Department of Wind Energy

Power performance testing
The modern ways

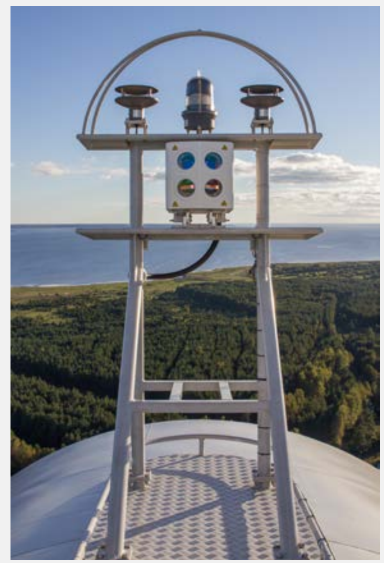
Remote sensing instruments

–

Future/Now: use of **nacelle-based wind lidars**

ZephIR Dual Mode
(scanning)
by *ZephirLidar*

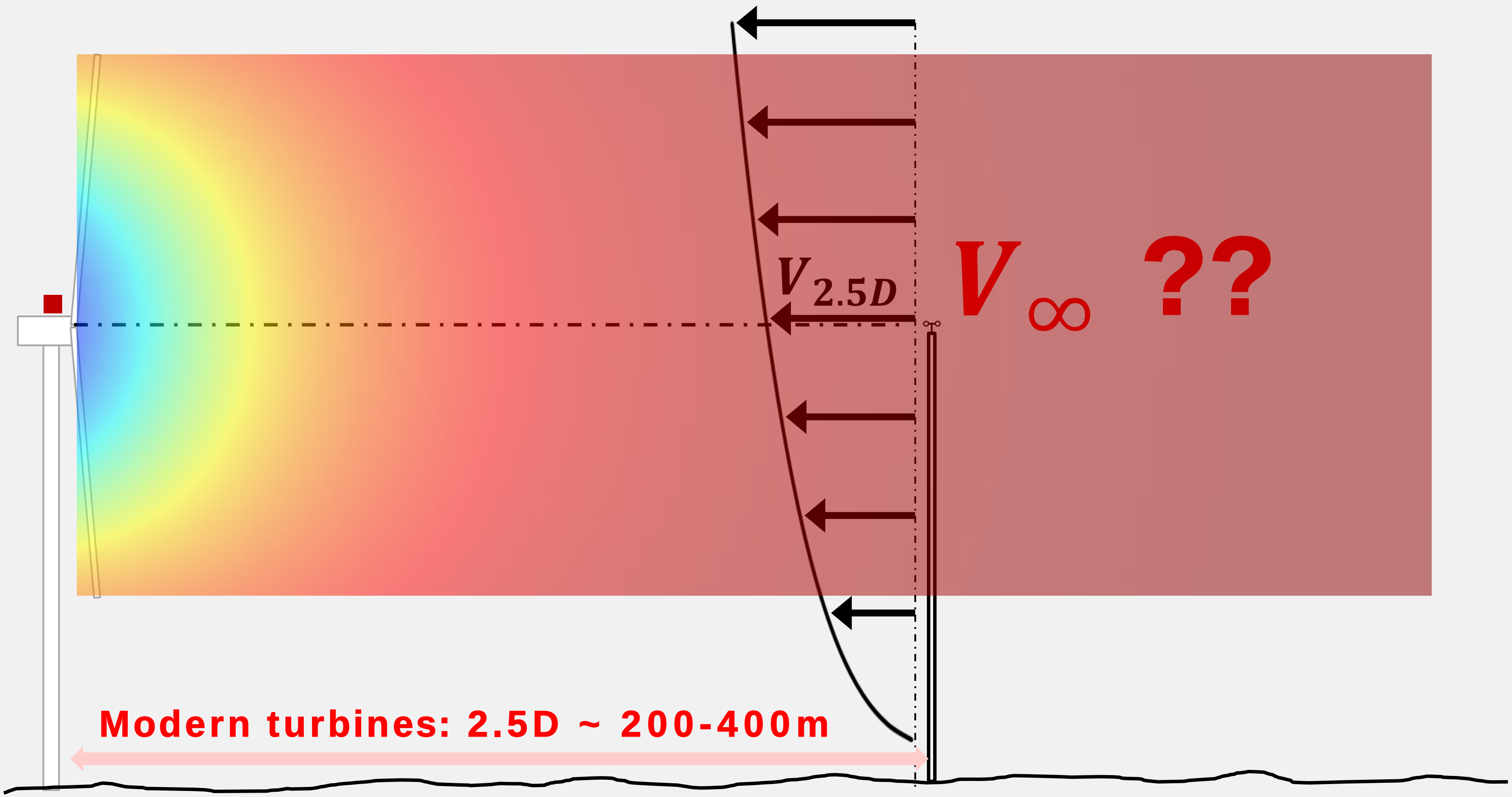
Wind Iris
(4-beam)
by *AventLidar*



Wind Eye
(4-beam)
by *Windar Photonics*

Diabrezza
(9-beam)
by *Mitsubishi Electric*

Searching for free stream wind speed

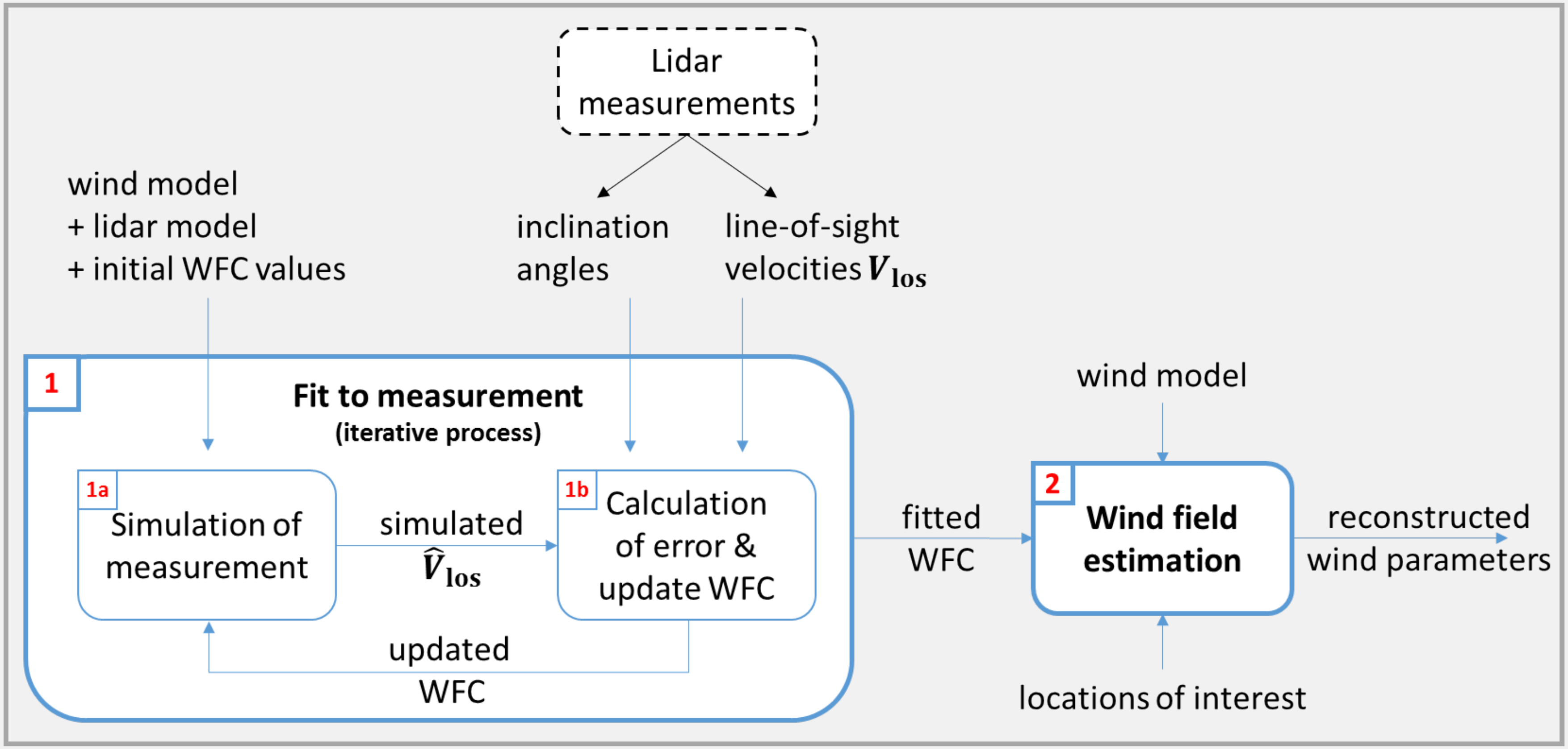


- Decorrelation WSpeed / power
- Hub height speed insufficient?
- 2.5D not really free wind …

Model-fitting Wind Field Reconstruction

- **Method is (not new…)**

Schlipf D., Rettenmeier A., Haizmann F., Hofsäß M., Courtney M. and Cheng, P. W.: "Model Based Wind Vector Field Reconstruction from Lidar Data", DEWEK, 2012.



- **need new "wind models" for profiling nacelle lidars, suitable for power performance testing**

What's wrong with 2.5D?

- **Lidar range capabilities**
  – Soon not sufficient for very large turbines
  – Or systems will become more expensive
- **Measurement / beam locations**
  – Are/will be too far away
    - to accept WFR assumptions: inhomogeneity, lack of coherence, etc
    - nac. lidars measure wind less and less representative to what the turbine feels
  – Affected by e.g. terrain or site features
- **"Decorrelation" issues might come back**
- **AND…**
  – **2.5D really is NOT free stream!**
  – Under-estimation of V_∞ by about 0.7%
    - According to models, confirmed by measurements
    - Should be accounted into AEP calculations…

Wind model accounting for shear

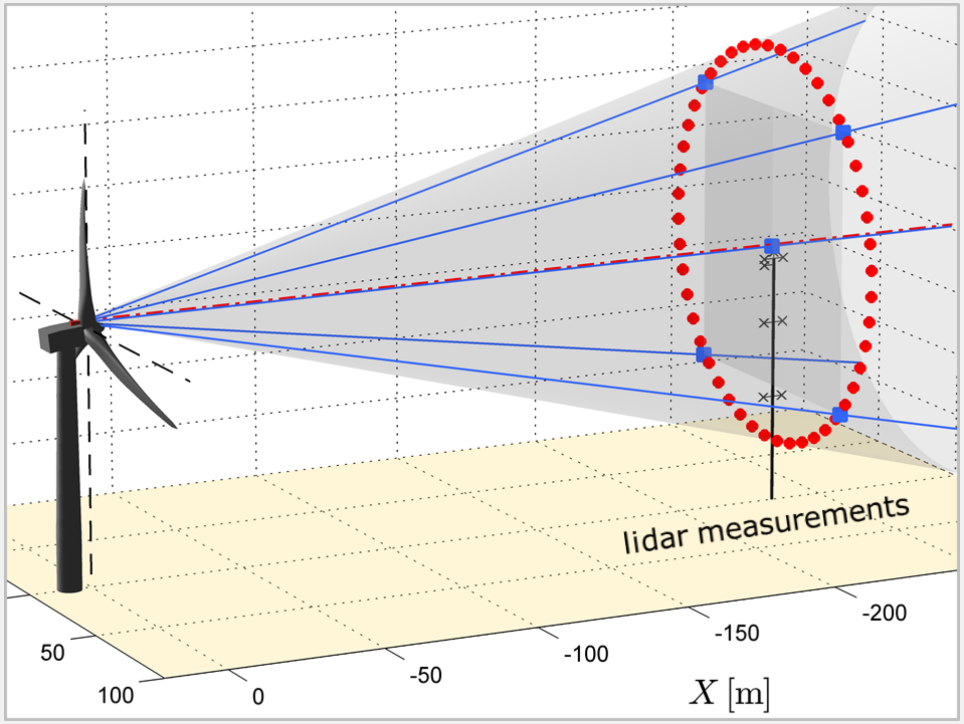
- Use lidar measurements at 2.5 rotor diameters
- “static” model: stationarity assumed
- Assumes horizontal homogeneity and power law shear profile

- **Fits three wind characteristics**

  ➔ wind speed $\mathbf{V_0}$ ($@H_{hub}$)

  \+ relative wind dir. $\boldsymbol{\theta_r}$ (yaw misalignment)

  \+ shear exponent $\boldsymbol{\alpha_{exp}}$



Combined wind-induction model

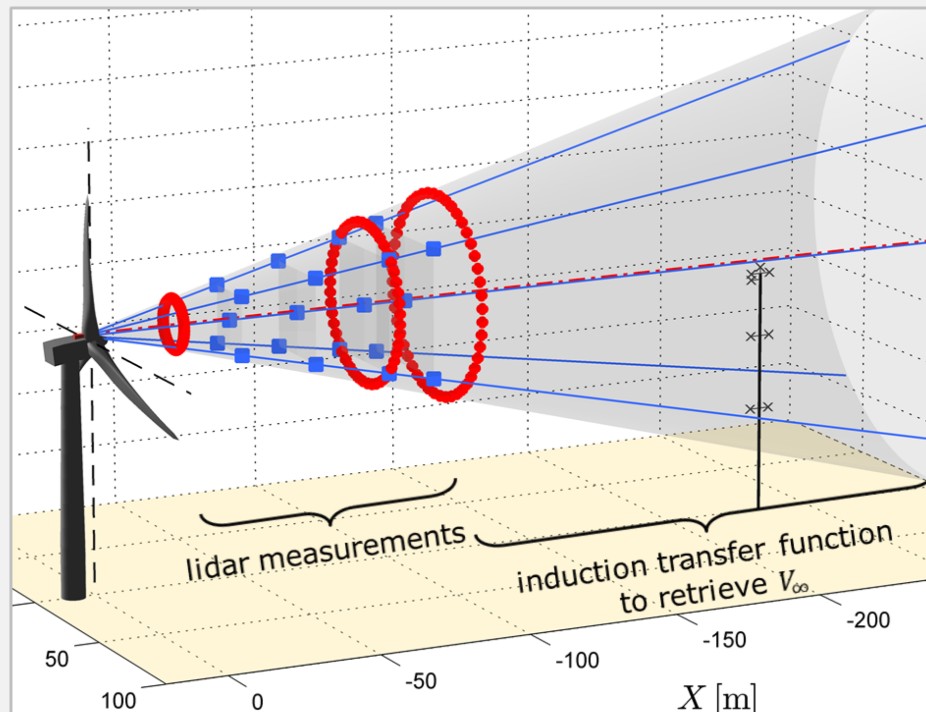
- Use lidar measurements at multiple distances close to rotor
- Additionally assumes simple induction model:

(from actuator disk and vortex sheet theory)

$$\frac{U(x)}{U_\infty} = 1 - a_{ind}\left(1 + \frac{\xi}{\sqrt{1+\xi^2}}\right)$$

- **Fits four wind characteristics**

➔ Free stream wind speed $\mathbf{V}_\infty$ (@H_{hub})
\+ relative wind dir. $\boldsymbol{\theta_r}$
\+ shear exponent $\boldsymbol{\alpha_{exp}}$
\+ induction factor $\boldsymbol{a_{ind}}$

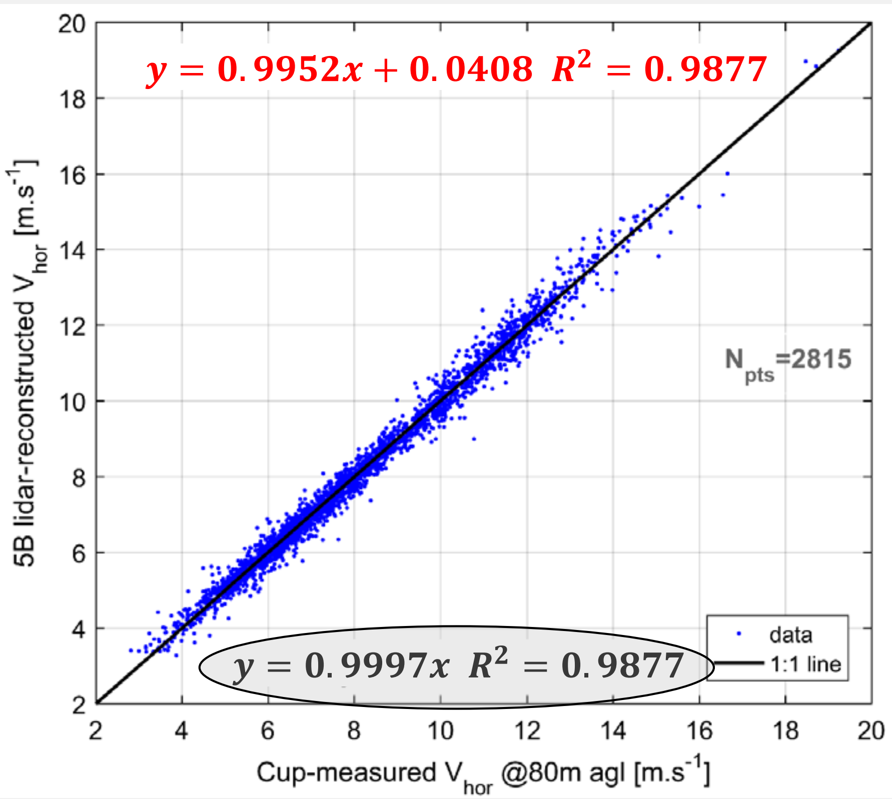


Wind speed results

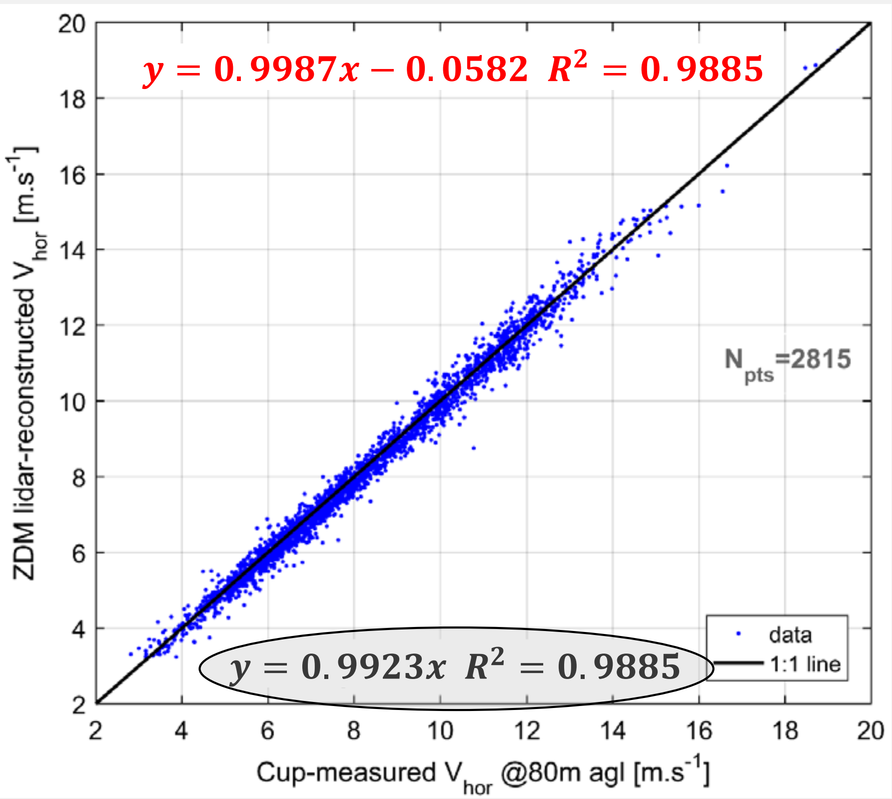
Mast comparison, WFR using the wind-induction model

- ➔ horizontal speed estimated @hub height and 2.5D_rot
- ➔ IEC "free sector": $[110°, 219°]$

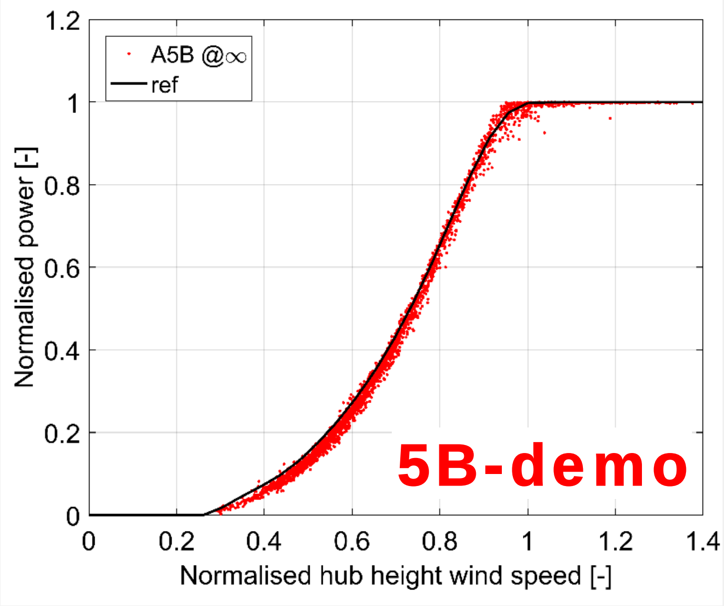
5B-demo: use the 5 LOS
4 dist, from 0.5 to @1.2D_rot

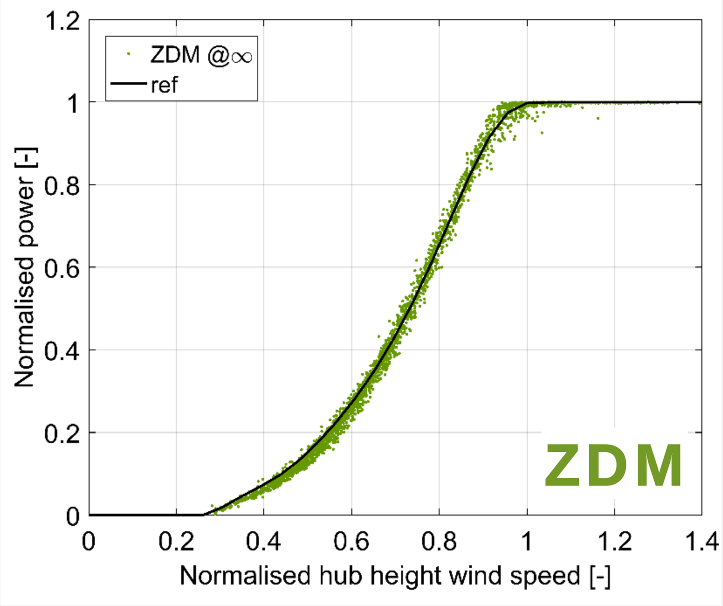


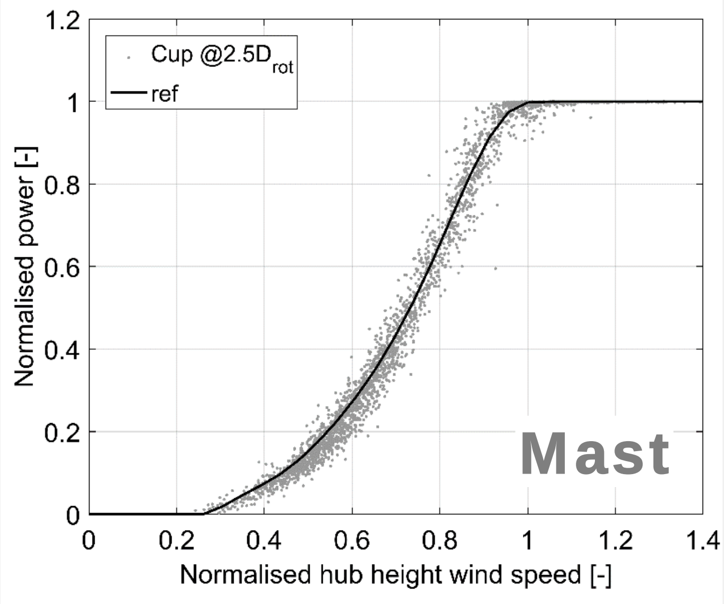
ZDM: use 6 LOS
3 dist., from 0.3 to 1.2D_rot



Measured Power curves (scatter)
WFR using wind-induction model







Challenges in PCV with nacelle lidars

- **Need to give directions to methods for wind field reconstruction**
  - WFR model is of critical importance for accurate wind estimates
  - What kind of shear/veer model?
  - How to quantify model inadequacy? (e.g. fitting residuals)
- **Rotor equivalent wind speed**
  - By integration of shear profile?
  - Some geometrical issues...
- **Accounting for terrain**
  - Elevation data integrated as inputs to the WFR codes?
  - Classification of terrain: different WFR models to recommend?
- **Practical questions**
  - integration of brackets into turbine design
  - alignment of nacelle lidar to rotor axis

Thanks for your attention!

Scientific article: *Wind Energy Science*

Research articles

Wind Field Reconstruction from Nacelle-Mounted Lidars Short Range Measurements

Antoine Borraccino[1], David Schlipf[2], Florian Haizmann[2], and Rozenn Wagner[1]
[1]DTU Wind Energy, Roskilde, Denmark
[2]Stuttgart Wind Energy, University of Stuttgart, Germany

My PhD thesis:

Remotely measuring the wind using turbine-mounted lidars

More info:

- website www.unitte.dk
- contact: borr@dtu.dk, rozn@dtu.dk

Does this make it any easier?

Flow disturbed by turbine wakes !

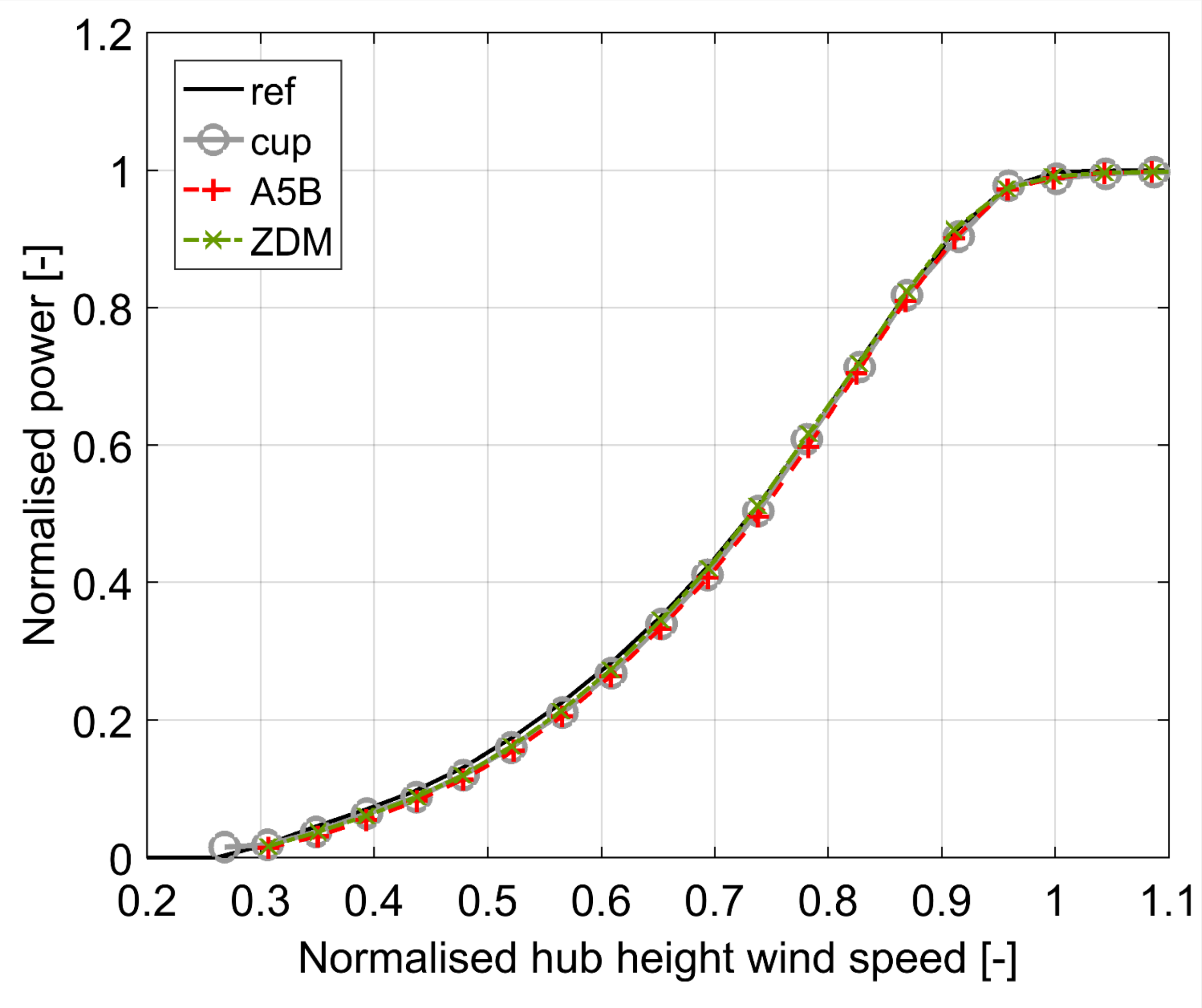
(very) complex terrain

Perdigão.
credit: N. Vasiljevic

Preparing for questions
-
Wind Field Reconstruction

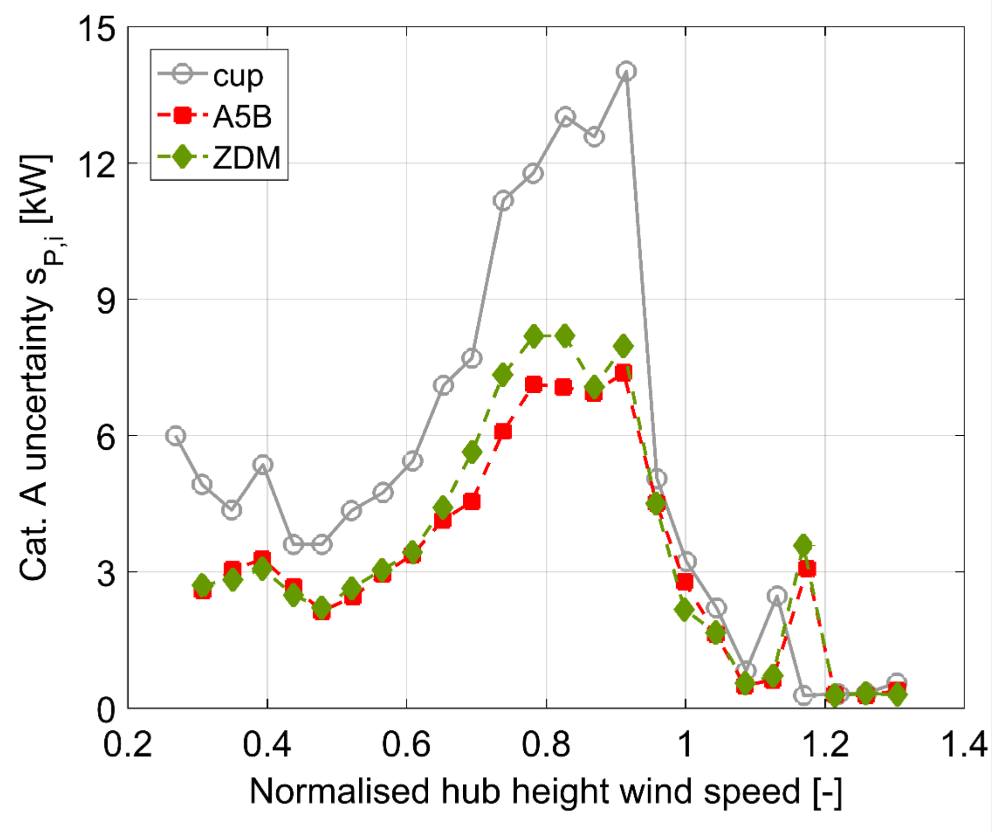
Measured Power curves (binned)

WFR using wind-induction model



Power curve uncertainties: power, type A
WFR using wind-induction model

- **Clear reduction of scatter in power curve**
  ➔ nacelle lidars yield smaller type A (statistical) power uncertainty

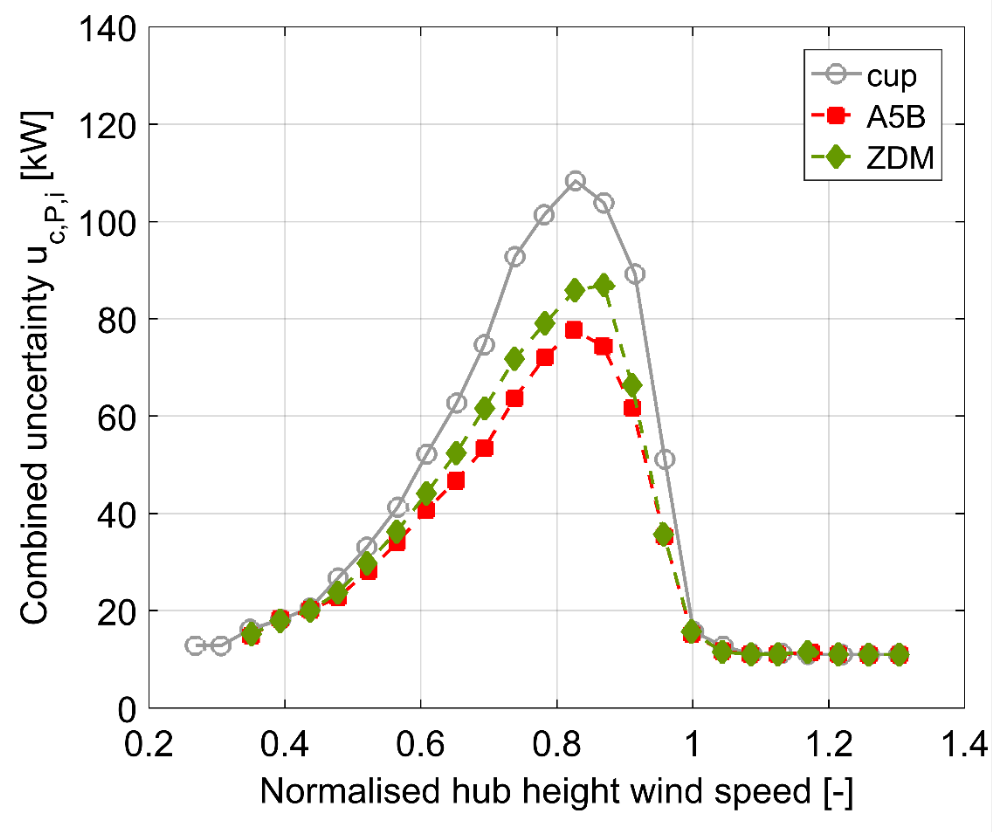


Power curve uncertainties: combined
WFR using wind-induction model

- **Results are mostly dependent on type B wind speed uncertainty**

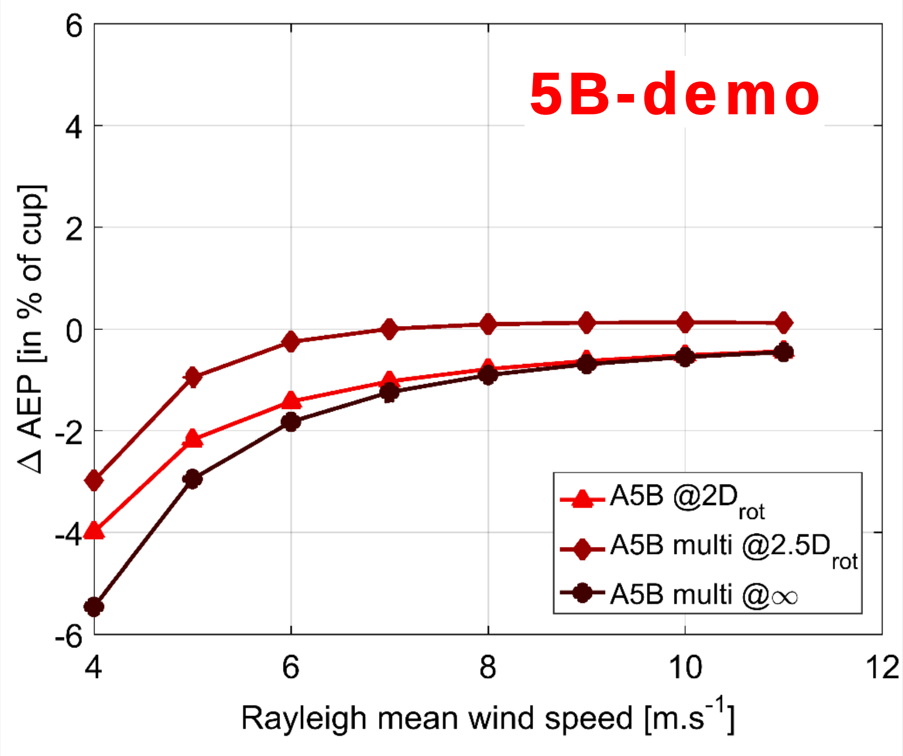
  ➔ very sensitive to the ”terrain uncertainty”

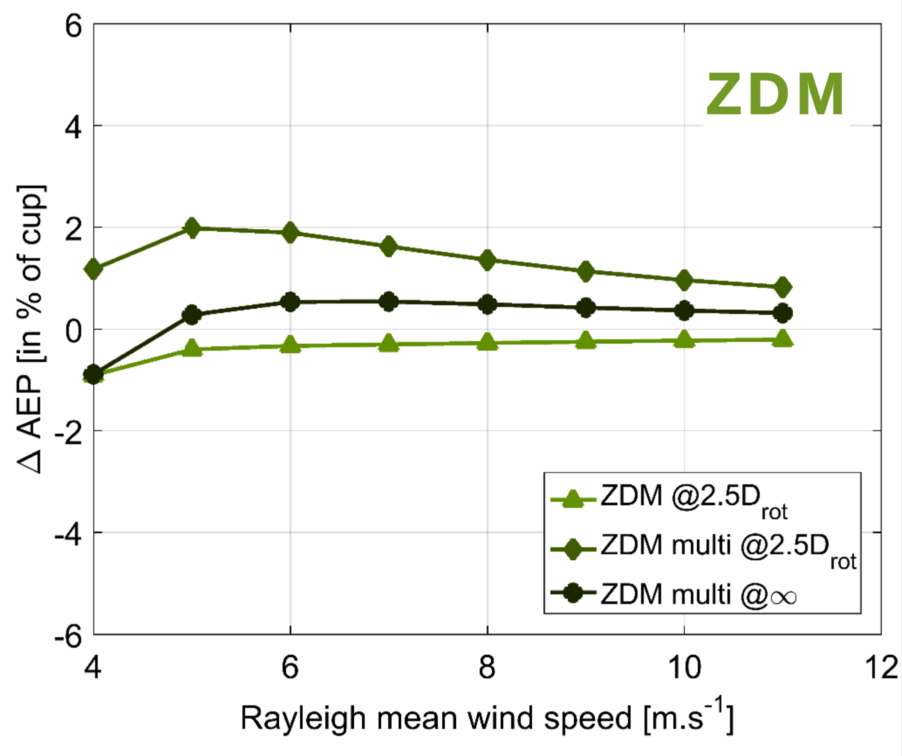
  ➔ lidar uncertainties are smaller only due to this component…



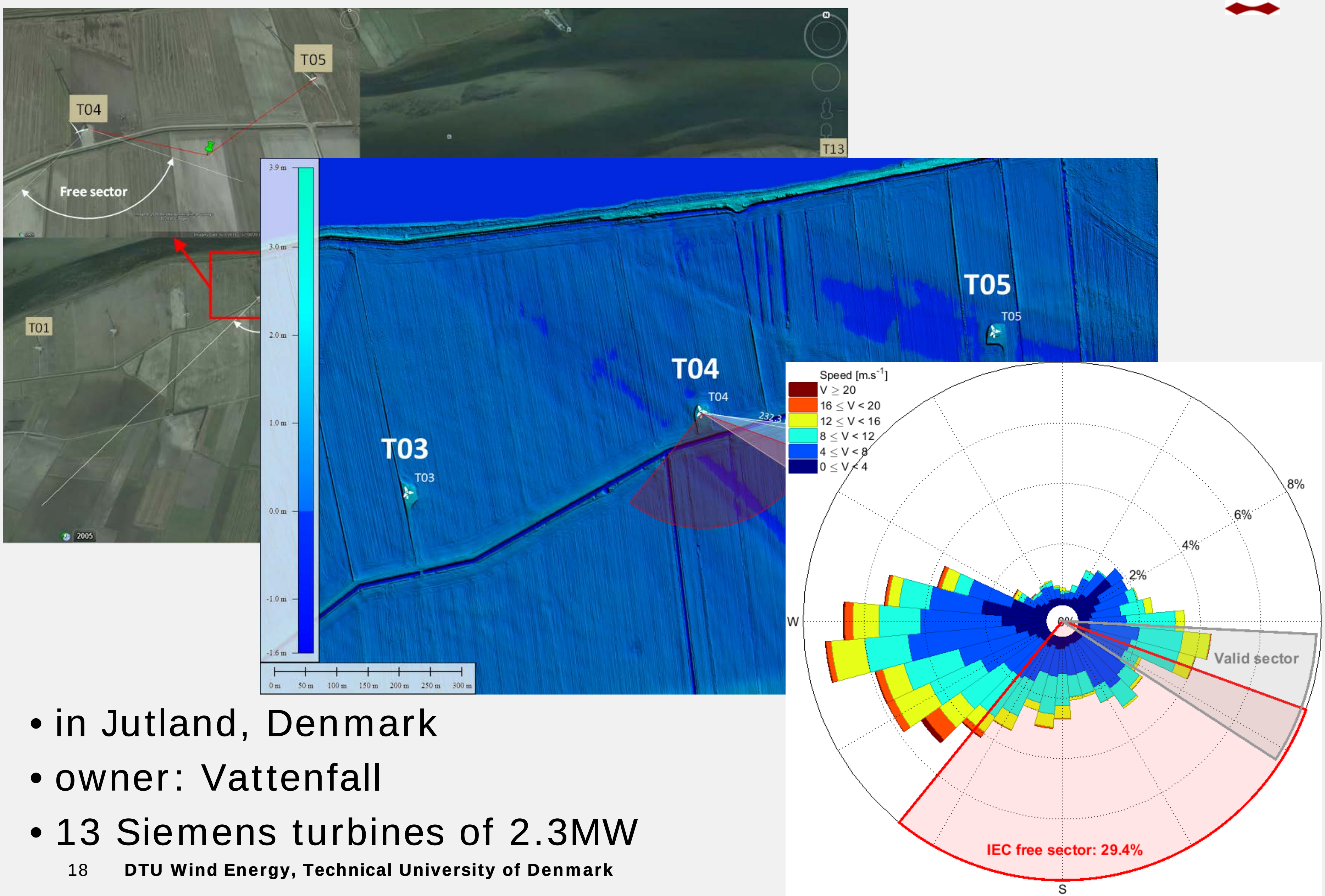
Annual Energy production

- **Derived as percentage of AEP using ”mast power curve”**
- **3 methods:**
  - Wind model
  - Combined wind-induction
    - Wind speed estimated at 2.5D
    - fitted free stream wind speed (V_∞)





Full-scale campaign: Nørrekær Enge



- in Jutland, Denmark
- owner: Vattenfall
- 13 Siemens turbines of 2.3MW

Wind speed results: summary table

Data filtering		Reconstruction case		Forced linear regressions results			
Case	Direction sector	Dataset	Lidar	Input measurement ranges	gain	R^2	Number of periods
1	$[93°, 123°]$	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0146	0.9936	885
			ZDM, 6 LOS	2.5 D_{rot}	1.0090	0.9938	
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0063	0.9944	
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9961	0.9947	

- Overestimation of 1-1.5% with the wind model
- Better performance of wind-induction model using the lidars' short-range measurements
- Lidar-to-lidar: 5B-Demo about 0.5-1% higher than ZDM

Wind speed results: summary table

Data filtering		Reconstruction case		Forced linear regressions results			
Case	Direction sector	Dataset	Lidar	Input measurement ranges	gain	R^2	Number of periods
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			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9961	0.9947	
2	$[93°, 123°]$	disjoint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0133	0.9953	1476
			ZDM, 6 LOS	2.5 D_{rot}	1.0080	0.9942	2143
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0057	0.9961	1123
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9965	0.9962	2659

- Disjoint datasets: similar observations
- Increased number of valid data points (2-3x more)
- R^2 enhanced slightly

Wind speed results: summary table

Data filtering		Reconstruction case	Forced linear regressions results				
Case	**Direction sector**	**Dataset**	**Lidar**	**Input measurement ranges**	**gain**	**R^2**	**Number of periods**
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			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9965	0.9962	2659
3	$[110°, 219°]$ (IEC free sector)	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0059	0.9848	2815
			ZDM, 6 LOS	2.5 D_{rot}	1.0028	0.9841	
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	0.9997	0.9877	
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9923	0.9885	

- Better agreement between lidar and mast
- Much larger scatter ("signal decorrelation")
- Still 5B-Demo above ZDM (about 0.5%)

Wind speed results: summary table

Data filtering			Reconstruction case	Forced linear regressions results			
Case	**Direction sector**	**Dataset**	**Lidar**	**Input measurement ranges**	**gain**	**R^2**	**Number of periods**
1	$[93°, 123°]$	Joint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0146	0.9936	885
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			ZDM, 6 LOS	2.5 D_{rot}	1.0080	0.9942	2143
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	1.0057	0.9961	1123
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9965	0.9962	2659
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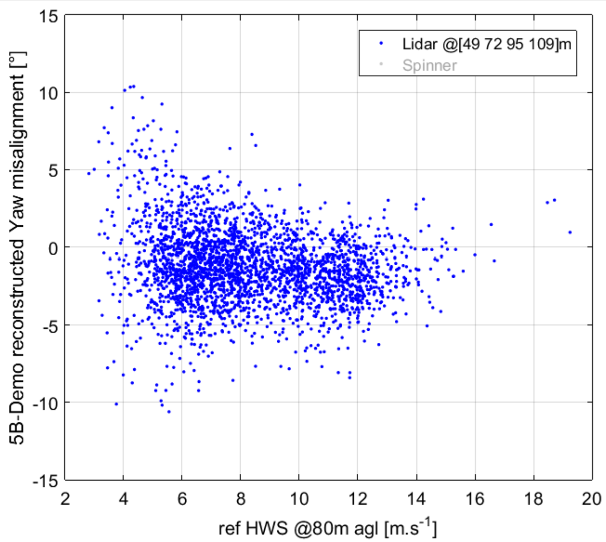
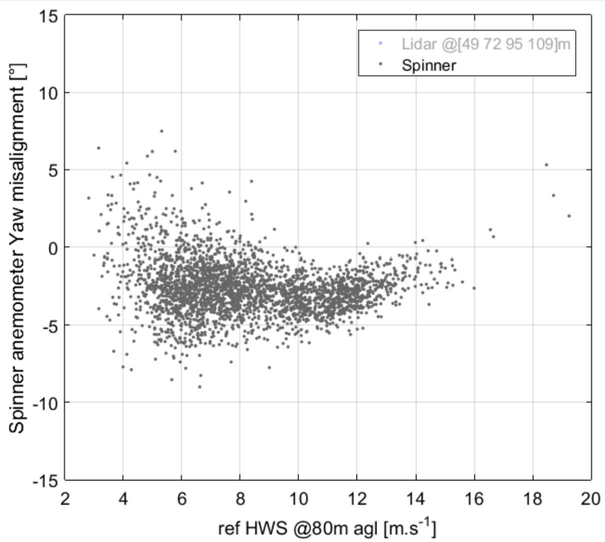
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9923	0.9885	
4	$[110°, 219°]$ (IEC free sector)	disjoint	5B-Demo, 5 LOS	2.0 D_{rot}	1.0041	0.9840	4588
			ZDM, 6 LOS	2.5 D_{rot}	1.0038	0.9860	5615
			5B-Demo, 5 LOS	from 0.5 to 1.15 D_{rot}	0.9988	0.9888	4099
			ZDM, 6 LOS	from 0.3 to 1.25 D_{rot}	0.9935	0.9897	6199

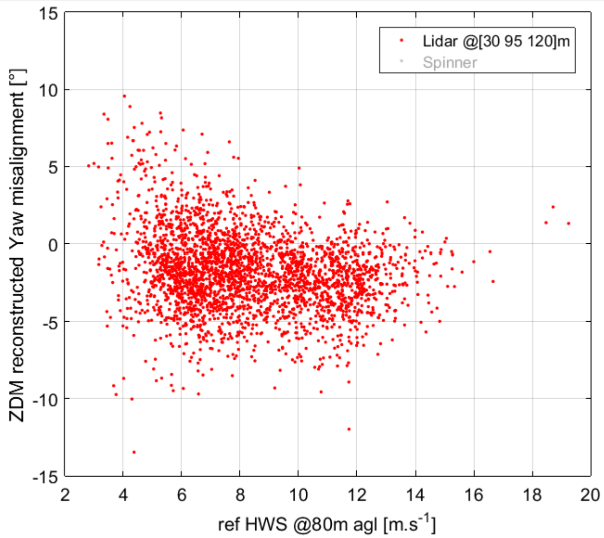
Yaw misalignment results:

WFR using the wind-induction model

- Wind sector: $[110°, 219°]$ (joint datasets)
- "Ref." yaw misalignment from spinner anemometer







5B-demo: 4 dist, from 0.5 to @1.2D_rot

Spinner anemometer

ZDM: 3 dist. From 0.3 to 1.2D_rot

➔ Higher scatter with lidars than spinner

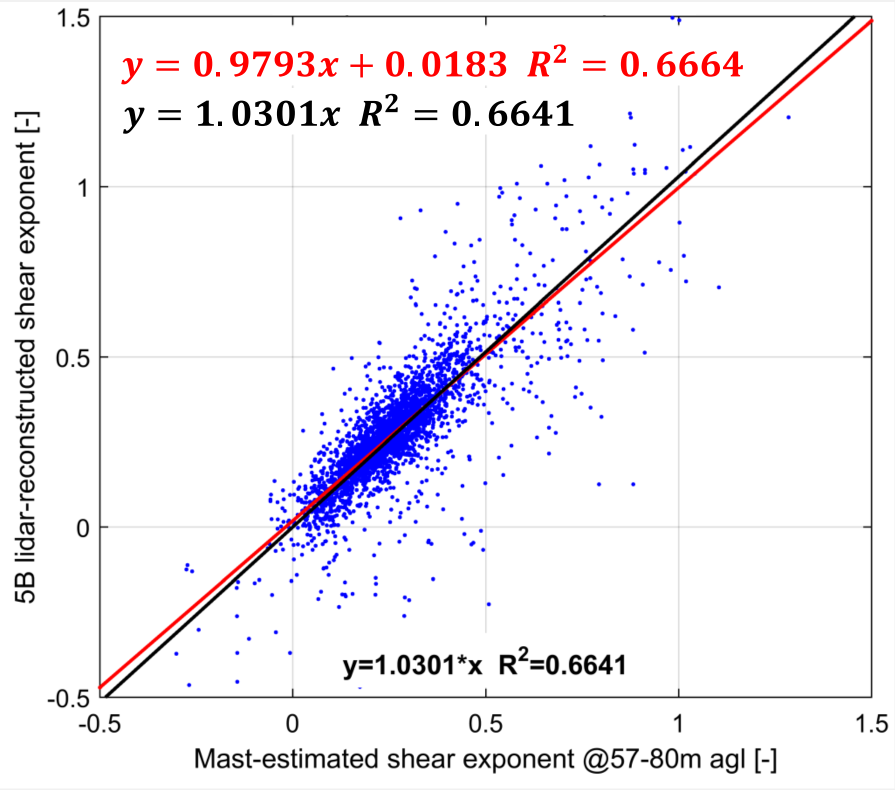
➔ "mean" yaw misalignment: $\approx -3°$

➔ The two nacelle lidars seem to provide similar results

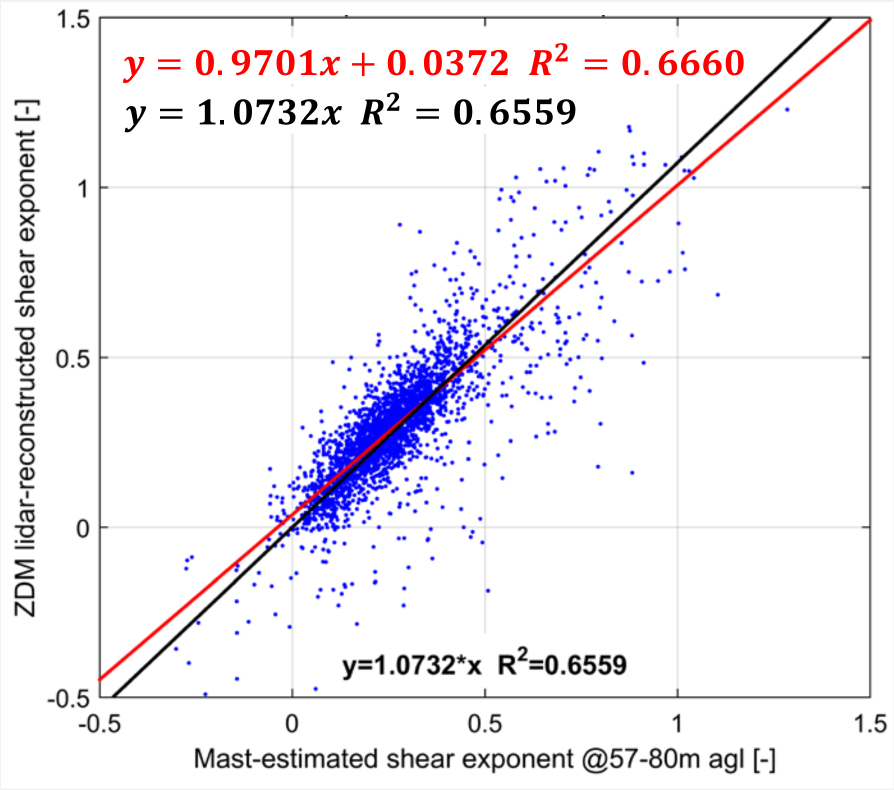
Shear exponent results:

WFR using the wind-induction model

- Wind sector : $[110°, 219°]$ (joint datasets)
- "Ref." shear exponent: from mast, using cups at 80 and 57m agl



5B-demo: 4 dist, from 0.5 to @1.2D_rot



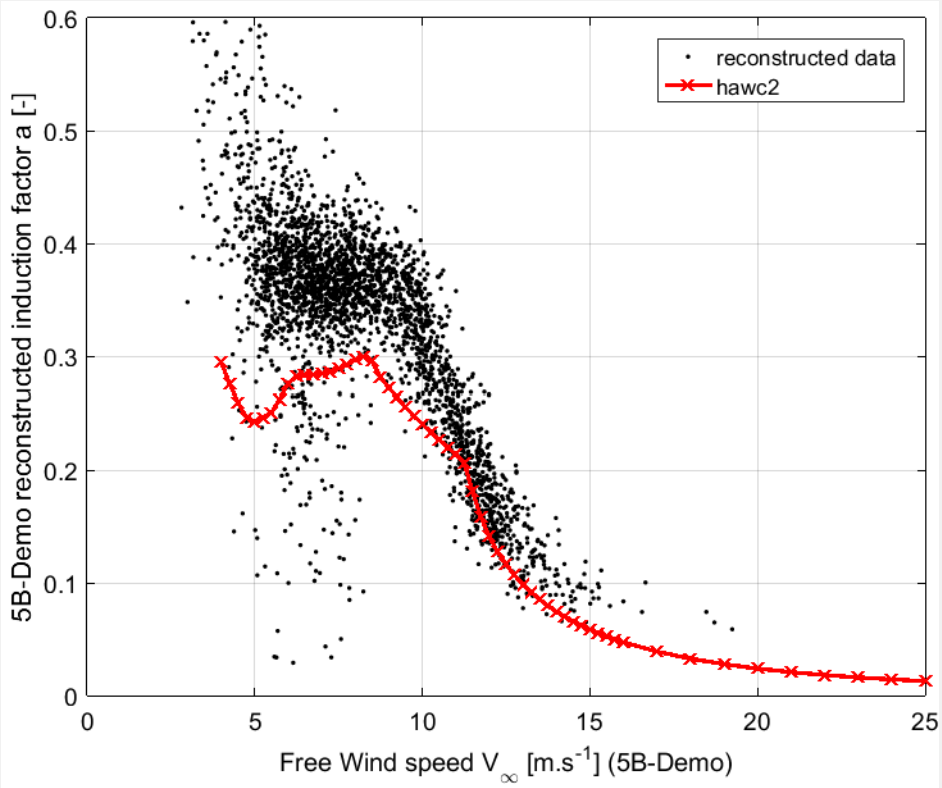
ZDM: 3 dist. From 0.3 to 1.2D_rot

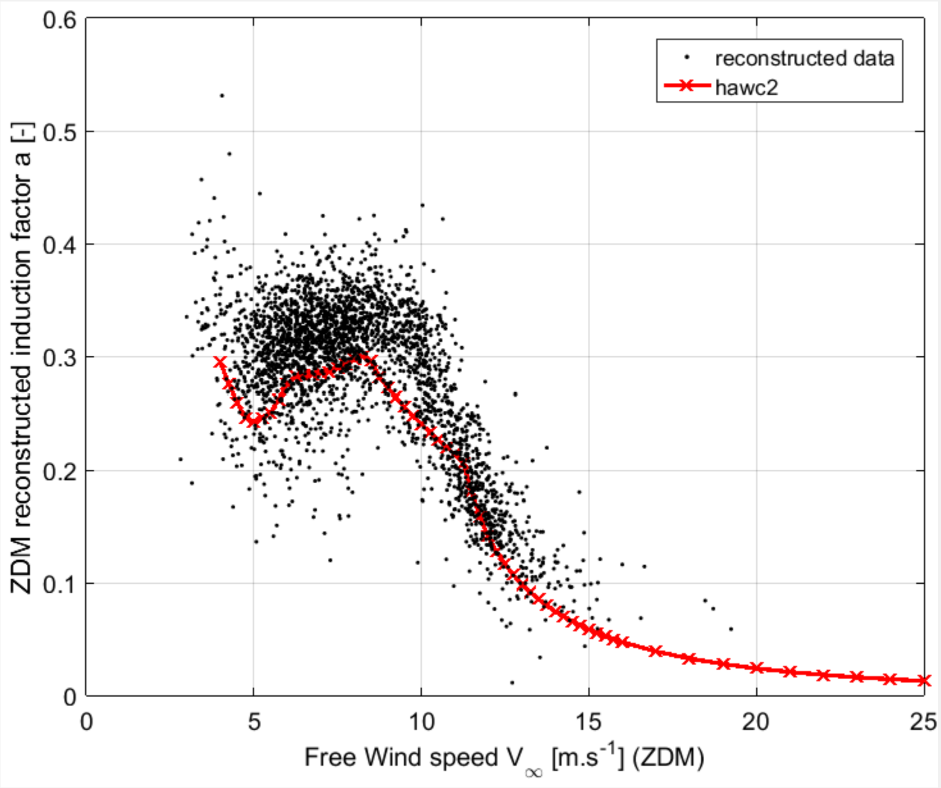
➔ Slight overestimation vs. mast ➔ Similar results between the two lidars

Induction factor results:

WFR using the wind-induction model

- Wind sector : $[110°, 219°]$ (joint datasets)
- "Ref." induction factor: C_T from "HAWC2" simu, $a = 0.5 \cdot \left(1 - \sqrt{1 - C_T}\right)$

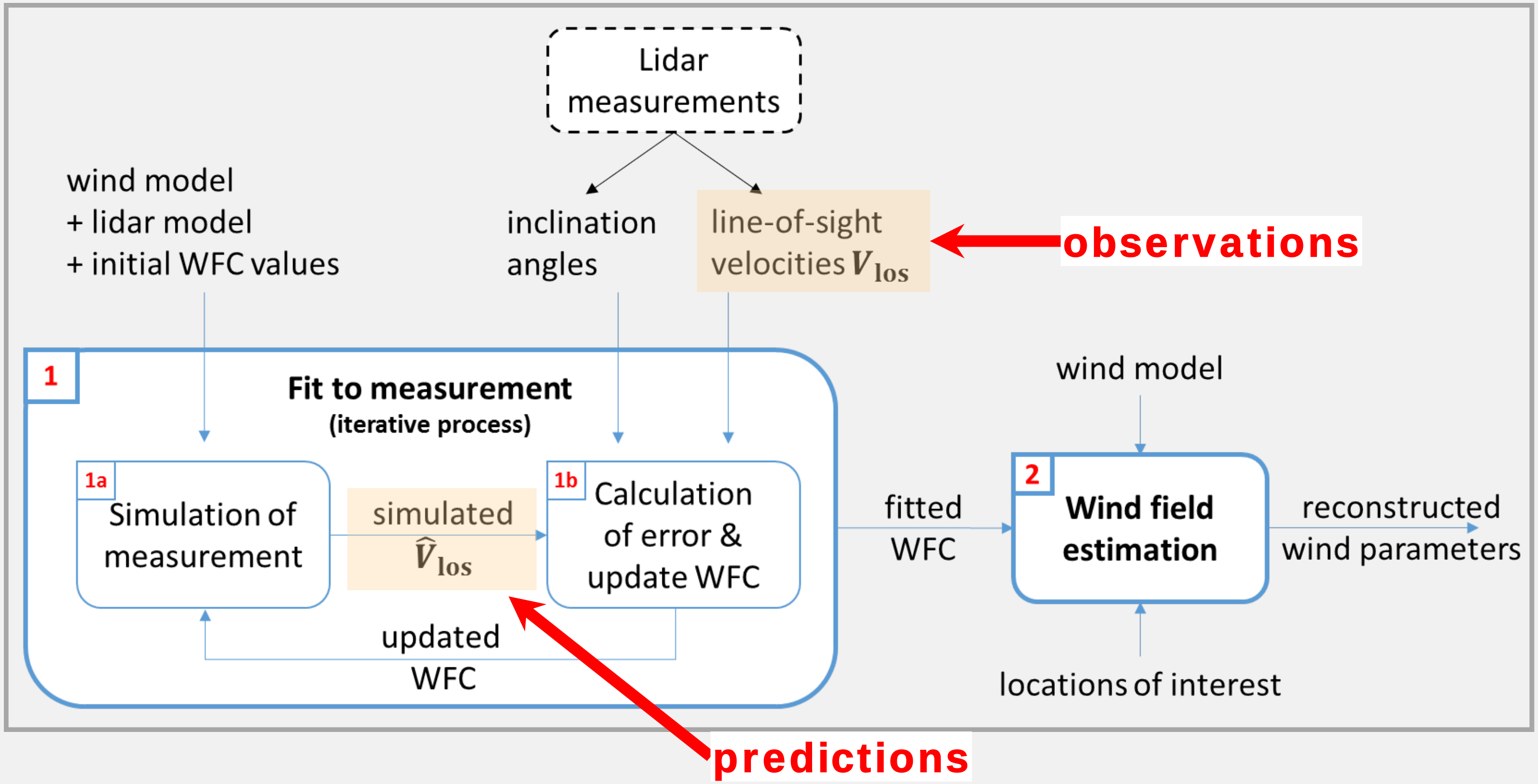




5B-demo: 4 dist,
from 0.5 to @1.2D_rot

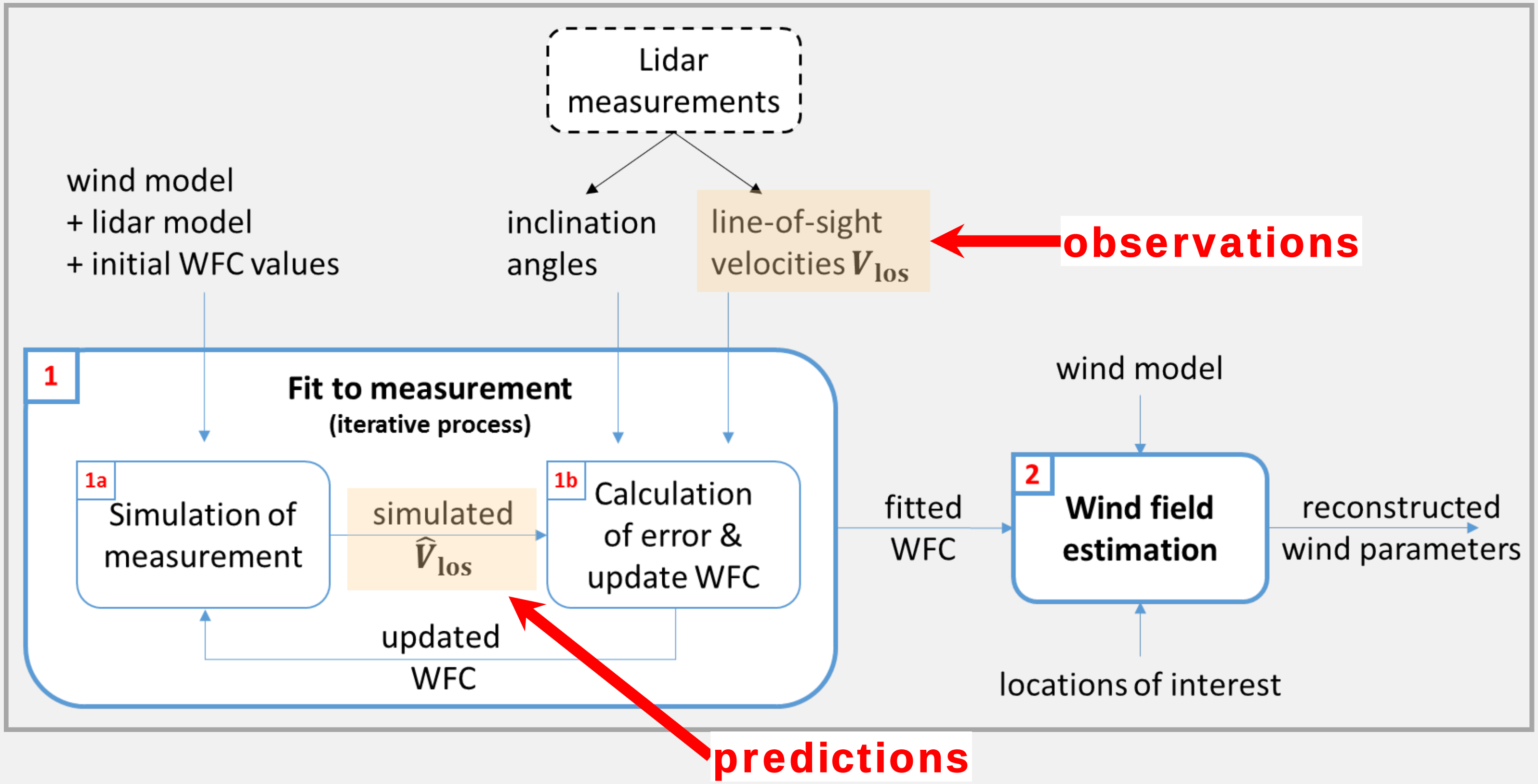
ZDM: 3 dist.
From 0.3 to 1.2D_rot

LOS velocity fitting residuals



- **Definitions:**
  - $\boldsymbol{V}_{\text{los}}$ and $\widehat{\boldsymbol{V}}_{\text{los}}$ are column vectors of length = N meas. points (e.g. 5B-Demo = 4 dist*5 los =20; ZDM = 3 dist*6 los =18)
  - "bias" $= \boldsymbol{V}_{\text{los}} - \widehat{\boldsymbol{V}}_{\text{los}}$; "error": $= \boldsymbol{abs}(\boldsymbol{V}_{\text{los}} - \widehat{\boldsymbol{V}}_{\text{los}})$

LOS velocity fitting residuals

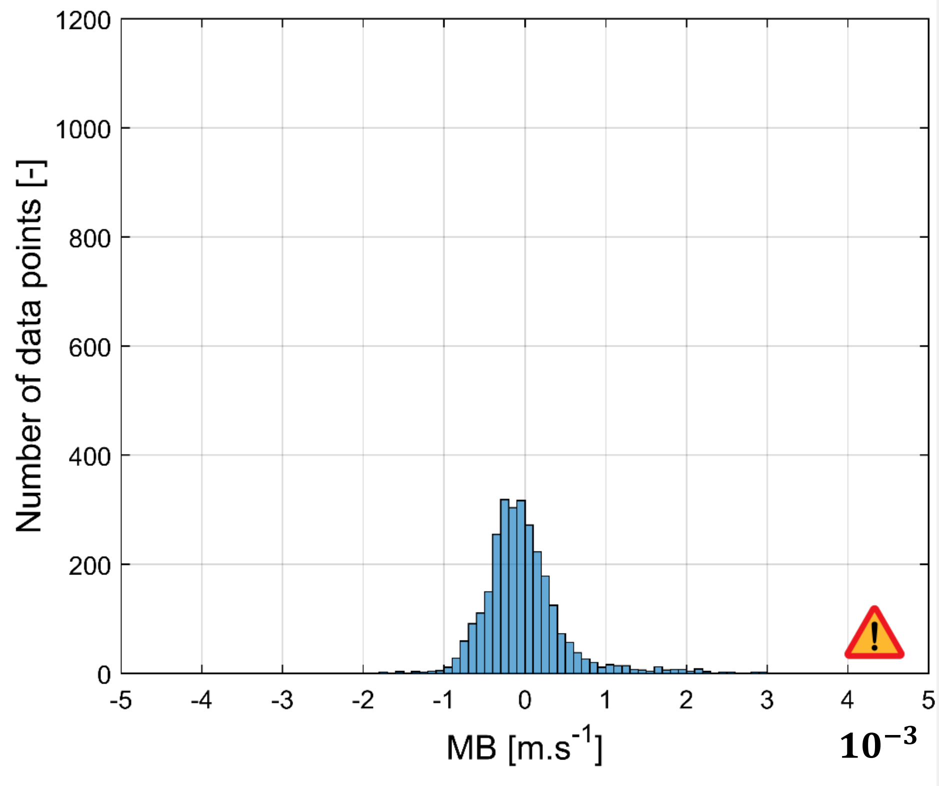


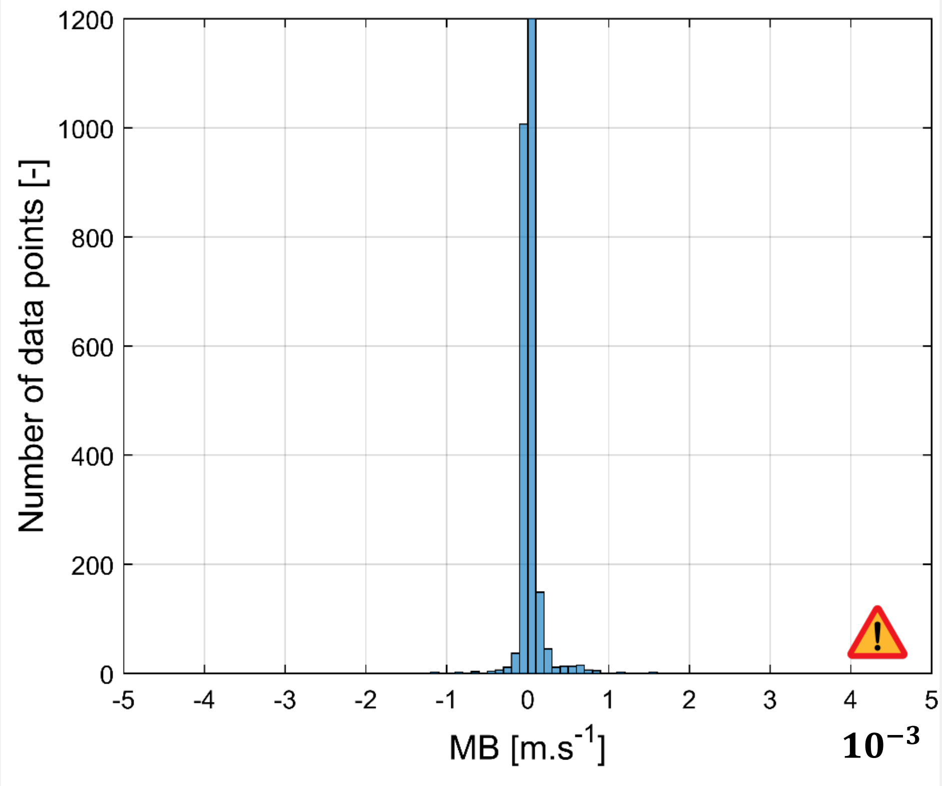
- **Computed stats:**
  - M: mean, N: normalised; F: fractional;
  - S: squared; R: root; SS: sum of squares
  - **MB**, ME, NMB, NME, MFB, MFE, SSE, MSE, **RMSE**, NMSE

V_los fitting residuals: mean bias

WFR using the wind-induction model

- Wind sector : $[110°, 219°]$ (joint datasets)





5B-demo
4 dist. from 0.5 to @1.2D_rot

ZDM
3 dist. from 0.3 to 1.2D_rot

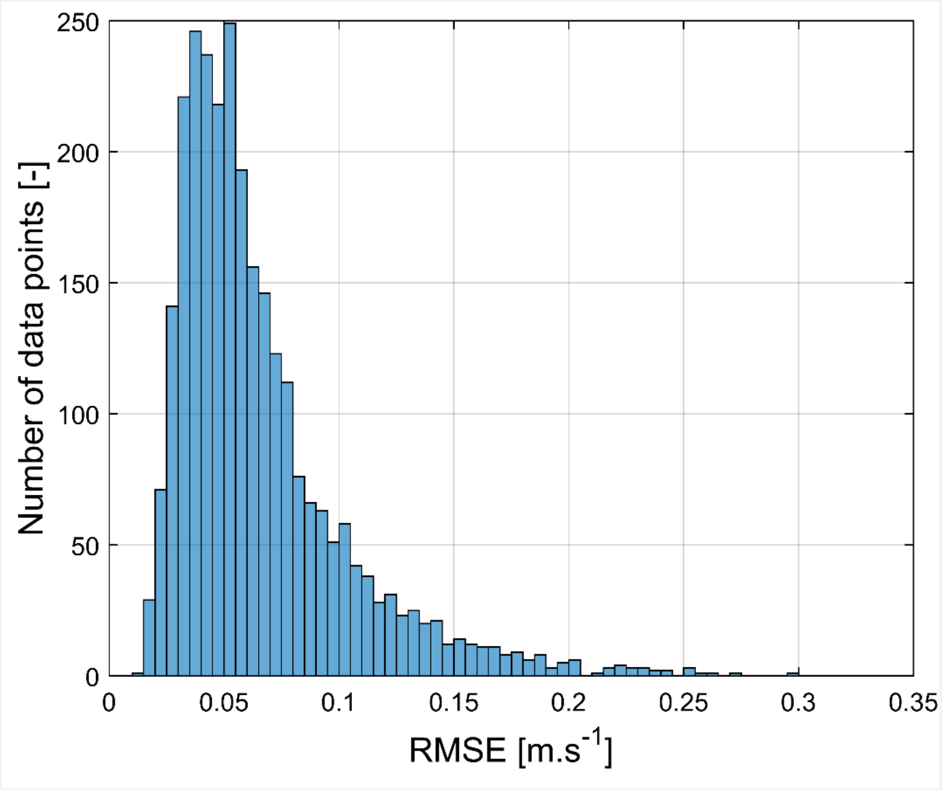
➔ MB show very low values;

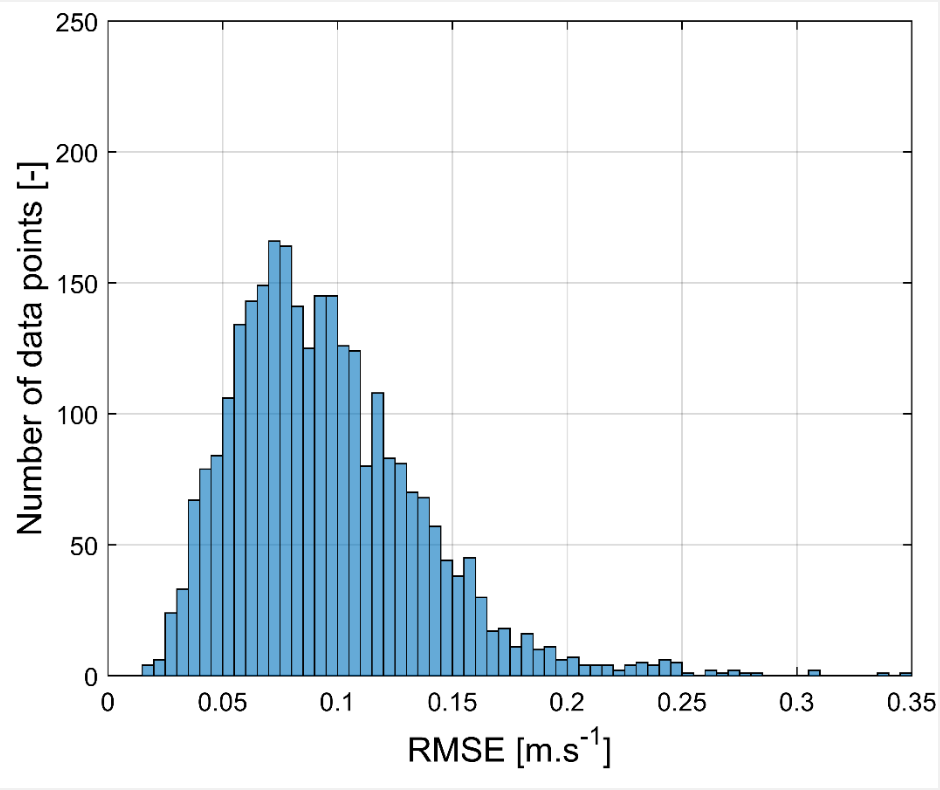
➔ Histogram centered on zero: the used model is “unbiased”

V_los fitting residuals: mean bias

WFR using the wind-induction model

- Wind sector : $[110°, 219°]$ (joint datasets)





5B-demo
4 dist. from 0.5 to @1.2D_rot

ZDM
3 dist. from 0.3 to 1.2D_rot

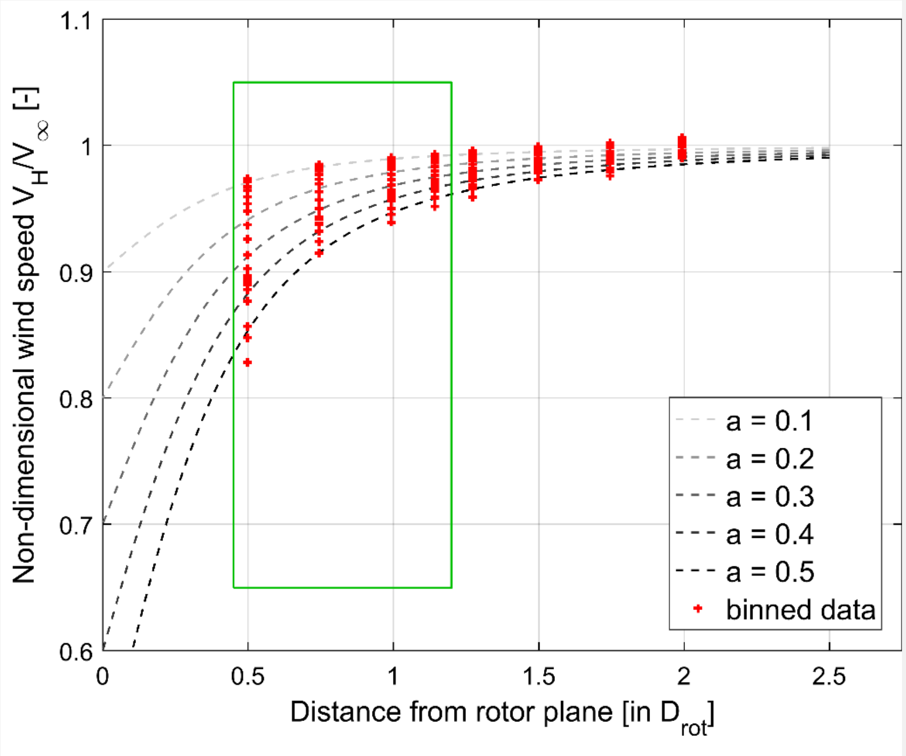
➔ RMSE values between 0 and 0.25 m/s

➔ Similar distributions for both lidars, with a slightly larger mean for ZDM

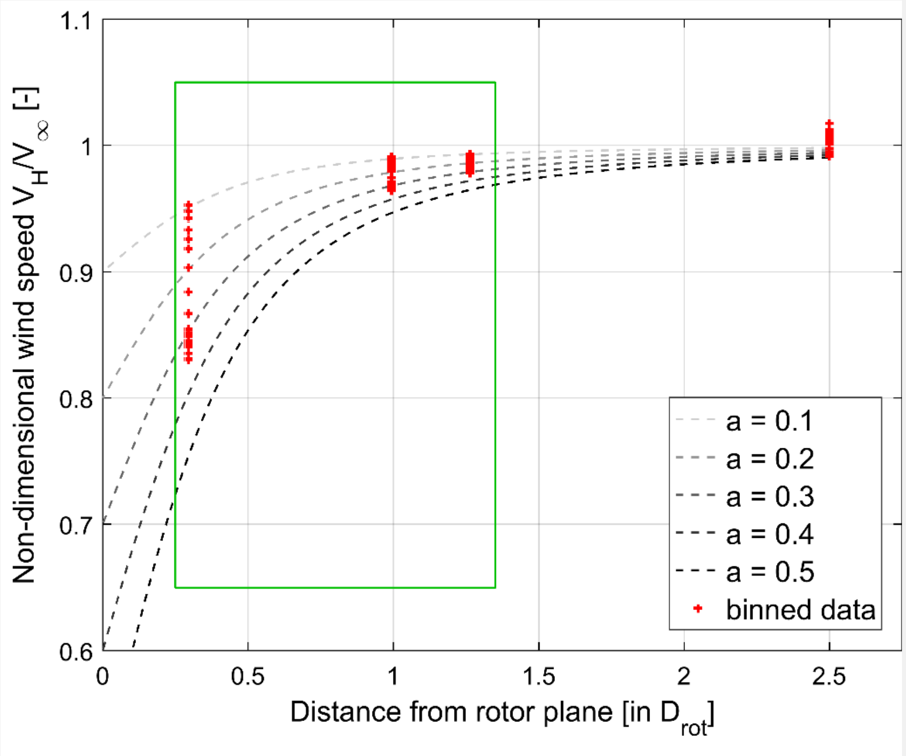
A simple induction model

- **Derived from the Biot-Savart law**
  - see *The upstream flow of a wind turbine: blockage effect*
  - two parameters: induction factor a, free wind speed U_∞

$$\frac{U}{U_\infty} = 1 - a\left(1 + \frac{\xi}{\sqrt{1+\xi^2}}\right), \text{ with } \xi = \frac{x_W}{R_{rot}}$$



5B-demo



ZDM

Simple induction models

- **One- or two- dimensional?**